Optimization of a Thin Film Solar Cell with Metallic Nanoparticles

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***Abstract*— In this paper the authors optimize the geometry of a thin solar cell with metallic nanoparticles by employing a finite element code to compute the light scattering from the cell and genetic algorithm optimization.**

***Index Terms*— Photovoltaic cells, Nanoparticles, Genetic Algorithms, Scattering, Computational electromagnetics, Finite element methods.**

I. INTRODUCTION

The study of the efficiency of solar cells made of photovoltaic (PV) layers is very important to the aim of reduce the use of fossil fuels.

Recently several researchers have demonstrated that the insertion of metallic nanoparticles within or near PV layers may improve significantly the efficiency of the solar cells.

In this paper the authors optimize the geometry of a thin solar cell by employing an FEM code to compute the light scattering from the cell and suitable genetic algorithms (GAs) for optimization.

II. FEM ANALYSIS OF LIGHT SCATTERING

Consider the thin film solar cell depicted in Fig. 1, in which hemi-ellipsoidal metallic nanoparticles, having semi-axes a, b and c, with a=b>c, are placed near a PV layer, having a thickness t. The particles centers are regularly placed at the nodes of a rectangular grid exhibiting the same grid step 2d along the x- and y-axis. To simplify the optimization the particles are assumed to have a given volume V=2abc/3, so that only one degree of freedom specifies their shape.

A monochromatic electromagnetic plane wave at optical frequency is incident normally on this system. For the sake of simplicity we assume that the wave is E-polarized along the x-axis.

For this electromagnetic scattering problem the Helmholtz vector equation holds:

$$\nabla\times\left(\mu_r^{-1}\nabla\times\overline{E}\right)-k_0^2\varepsilon_r\overline{E}=0 \qquad (1)$$

where μ_r and ε_r are the relative magnetic permeability and electrical permittivity, respectively and k_0 is the free-space wavenumber, given by:

$$k_0=\omega\sqrt{\varepsilon_0\mu_0}\ , \qquad (2)$$

with ω being the angular frequency and μ_0 and ε_0 the free-space permeability and permittivity, respectively.

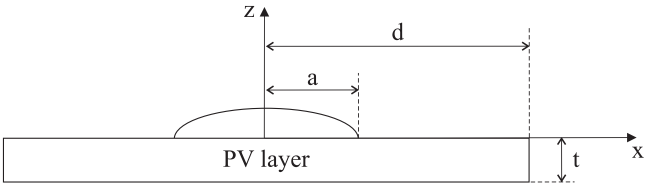

Fig. 1. Solar cell with a hemi-ellisoidal metallic nanopartcle.

For symmetry reasons the analysis can be restricted to the domain 0<x<d, 0<y<d, by imposing homogeneous Dirichlet boundary conditions on the x=0 and x=d planes and homogeneous Neumann ones on the y=0 and y=d planes. On the z direction the domain is truncated by means of two PML layers (not shown in Fig.1), one over and one under the cell. The analysis domain is discretized by means of tetrahedral edge finite elements.

At optical frequencies the metallic nanoparticles give rise to plasmons oscillations, which are taken into account by modeling the metal by means of a complex relative electric permittivity (Drude model) [1], given by:

$$\varepsilon_r=-\frac{\omega_p^2-(\omega^2+\nu^2)}{\omega^2+\nu^2}-j\frac{\nu\omega_p^2}{\omega(\omega^2+\nu^2)} \qquad (3)$$

where ω_p is the plasma frequency of the free electrons and ν is the relaxation frequency, the values of which are experimentally determined [2]. Note that at the optical frequencies of interest, the real part of the relative electric permittivity is negative. Assuming a unitary relative magnetic permeability, the FEM analysis is easily performed [3, 4].

In postprocessing the following non dimensional quantity is computed:

$$f(a,d,t)=\frac{W_i-W_o-W_j}{S_{inc}d^2} \qquad (4)$$

where W_i is the flux of the Poynting vector through a square surface over the cell, W_o is the same flux through a square surface under the cell, W_j is the Joule loss in the metallic particle and S_{inc} is the Poynting vector module of the incident wave.

III. OPTIMIZATION BY GENETIC ALGORITHMS

By employing the quantity in (4) as objective function to be maximized, a stochastic optimization is started by assuming the following data:

Metal of the nanoparticles: silver
Nanoparticle volume $V = 25600\ \mathrm{nm}^3$
Light Wavelengtht: $\lambda = 900$ nm
PV layer permittivity: $\varepsilon_r = 4$
PV layer permeability: $\mu_r = 1$

The geometrical parameters to be optimized are assumed to vary in the following ranges:

$$25\ \mathrm{nm} < a < 55\ \mathrm{nm}$$
$$40\ \mathrm{nm} < d < 250\ \mathrm{nm}$$
$$5\ \mathrm{nm} < t < 100\ \mathrm{nm}$$

The stochastic optimization was pursued by means of Genetic Algorithms (GAs), which are search algorithms which simulate the random evolution of populations of biological entities. These well-known algorithms have proven to be very efficient in optimizing electromagnetic devices [5, 6] both for low and high frequency applications. In this paper GAs have been used with the following characteristics [7]:

Population size: P=30
Number of generations: Ng=30
Binary lengths: Na=5, Nd=7, Nt=6
Selection: tournament selection with elitism
Crossover type: two-point crossover
Crossover probability at generation k:

$$Pc_k = 0.3 + 0.4(k-1)/(Ng-1)$$

Mutation probability at generation k:

$$Pm_k = 0.05 - 0.04(k-1)/(Ng-1)$$

As far as representation is concerned, the three geometric variables a, d, and t, were coded into binary strings of five, seven and six bits, respectively, giving a total of N=18 bits.

The reproduction process, which randomly creates a new generation from the old one, was chosen by tournament selection with a shuffling technique to choose random pairs.

The crossover process, by means of which individuals exchange chromosomes from one generation to the other, was two-point crossover with a probability P_c linearly varying from 0.3 to 0.7 while optimization goes on.

The mutation process, by means of which some random flips in the chromosomes of an individual are made, was employed with a probability P_m linearly decreasing from 0.05 to 0.01 while optimization proceeds.

The evolution was halted after 30 generations, reaching an optimal function value f_{max}=3.011, in relation to the following parameter configuration (values rounded to 0.5 nm):

$$a = 42\,\mathrm{nm}, \quad d = 61.5\ \mathrm{nm}, \quad t = 11\,\mathrm{nm}$$

In Fig. 2 the best (maximum) values of the objective function are plotted through the various generations. Fig. 3 shows the behaviour of (4) vs. wavelength (nm) for the best configuration.

The computations were performed by means of ELFIN, a large FEM code developed by the authors for electromagnetic CAD research [8].

More details and example will be provided in the full paper.

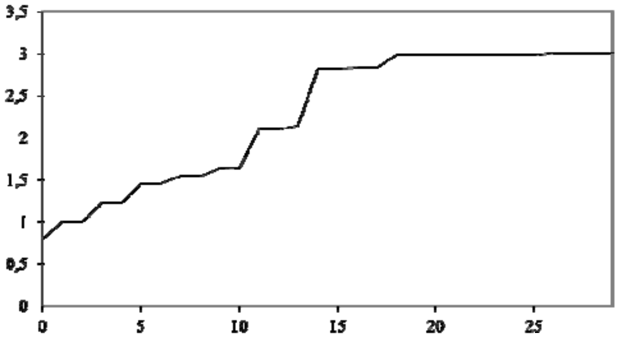

Fig. 2. Best objective function f over GA generations.

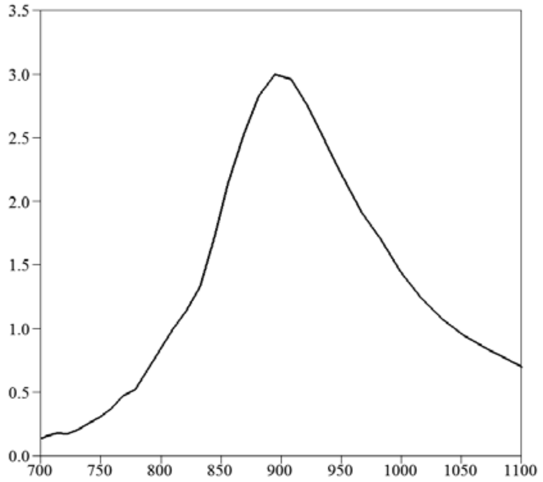

Fig. 3. Values of f vs. wavelength (nm) for the best configuration.

ACKNOWLEDGEMENTS

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